

# 1. U.S. Emissions of Greenhouse Gases in Perspective

## About This Report

The Energy Information Administration (EIA) is required by the Energy Policy Act of 1992 to prepare a report on aggregate U.S. national emissions of greenhouse gases for the period 1987-1990, with annual updates thereafter. This report is the eighth annual update, covering national emissions over the period 1990-1999, with preliminary estimates of emissions for 2000. The methods used by EIA to estimate national emissions of greenhouse gases are subject to continuing review. As better methods and information become available, EIA revises both current and historical emissions estimates (see "What's New in This Report," page 3). Emissions estimates for carbon dioxide are reported in metric tons carbon equivalent; estimates for other gases are reported in metric tons of gas (see "Units for Measuring Greenhouse Gases," page 2). Total national emissions estimates measured in carbon equivalents are shown in Table ES2.

Chapter 1 of this report briefly summarizes some background information about global climate change and the greenhouse effect and discusses important recent developments in global climate change activities. Chapters 2 through 4 cover emissions of carbon dioxide, methane, and nitrous oxide, respectively. Chapter 5 focuses on emissions of engineered gases, including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Chapter 6 describes potential sequestration and emissions of greenhouse gases as a result of land use changes.

## The Greenhouse Effect and Global Climate Change

The Earth is warmed by radiant energy from the Sun. Over time, the amount of energy transmitted to the Earth's surface is equal to the amount of energy re-radiated back into space in the form of infrared

radiation, and the temperature of the Earth's surface stays roughly constant; however, the temperature of the Earth is strongly influenced by the existence, density, and composition of its atmosphere. Many gases in the Earth's atmosphere absorb infrared radiation re-radiated from the surface, trapping heat in the lower atmosphere. Without the natural greenhouse effect, it is likely that the average temperature of the Earth's surface would be on the order of -19° Celsius, rather than the +14° Celsius actually observed.<sup>1</sup> The gases that help trap the Sun's heat close to the Earth's surface are referred to as "greenhouse gases." All greenhouse gases absorb infrared radiation (heat) at particular wavelengths.

The most important greenhouse gases are water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and several engineered gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF<sub>6</sub>). Water vapor is by far the most common, with an atmospheric concentration of nearly 1 percent, compared with less than 0.04 percent for carbon dioxide. The effect of human activity on global water vapor concentrations is considered negligible, however, and anthropogenic emissions of water vapor are not factored into national greenhouse gas emission inventories for the purposes of meeting the requirements of the United Nations Framework Convention on Climate Change (UNFCCC) or the Kyoto Protocol.<sup>2</sup> Concentrations of other greenhouse gases, such as methane and nitrous oxide, are a fraction of that for carbon dioxide (Table 1).

Scientists recognized in the early 1960s that concentrations of carbon dioxide in the Earth's atmosphere were increasing every year. Subsequently, they discovered that atmospheric concentrations of methane, nitrous oxide, and many engineered chemicals also were rising. Because current concentrations of greenhouse gases keep the Earth at its present temperature, scientists began to postulate that increasing concentrations of greenhouse gases would make the Earth warmer.

<sup>1</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 89-90. See also web site [www.ipcc.ch](http://www.ipcc.ch).

<sup>2</sup>The United Nations Framework Convention on Climate Change, which "entered into force" in 1994, calls on Annex I countries, including the United States, to return their greenhouse gas emissions to 1990 levels by the year 2000. The Kyoto Protocol, adopted in December 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries for the 2008 to 2012 commitment period that are collectively about 5 percent lower than the 1990 emissions of those countries. The Protocol has not yet "entered into force," which would require 55 countries and Annex I signatories with carbon dioxide emissions totaling 55 percent of total 1990 Annex I emissions to ratify the Protocol. The United States, at UNFCCC negotiations at Bonn, Germany, in July 2001, indicated that it considers the Kyoto Protocol to be flawed and stated that it has no plans, at this time, to ratify the Protocol.

In computer-based simulation models, rising concentrations of greenhouse gases nearly always produce an increase in the average temperature of the Earth. Rising temperatures may, in turn, produce changes in weather

and in the level of the oceans that might prove disruptive to current patterns of land use and human settlement, as well as to existing ecosystems. To date, however, it has proven difficult to disentangle the

**Table 1. Global Atmospheric Concentrations of Selected Greenhouse Gases**

Item	Carbon Dioxide	Methane	Nitrous Oxide	Sulfur Hexafluoride	Perfluoromethane
	(parts per million)			(parts per trillion)	
Pre-industrial (1750) Atmospheric Concentration . .	278	0.700	0.270	0	40
1998 Atmospheric Concentration . . . . .	365	1.745	0.314	4.2	80
Average Annual Change, Recent Years <sup>a</sup> . . . . .	1.5 <sup>b</sup>	0.007 <sup>b</sup>	0.0008	0.2	1.0
Atmospheric Lifetime (Years) . . . . .	50–200 <sup>c</sup>	12 <sup>d</sup>	114 <sup>d</sup>	3,200	>50,000

<sup>a</sup>Rate is calculated over the period 1990 to 1999.

<sup>b</sup>Rate has fluctuated between 0.9 and 2.8 parts per million per year for CO<sub>2</sub> and between 0 and 0.013 parts per million per year for methane over the 1990 to 1999 period.

<sup>c</sup>No single lifetime can be defined for CO<sub>2</sub> because uptake rates differ for different removal processes.

<sup>d</sup>This lifetime has been defined as an “adjustment time” that takes into account the indirect effect of the gas on its own residence time.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 244.

## Units for Measuring Greenhouse Gases

In this publication, EIA reports information in forms that are most likely to be familiar to users of the document. Therefore, energy and industrial data are reported in their native units. For example, oil production is reported in thousand barrels per day, and energy production and sales are reported in British thermal units (Btu). For readers familiar with metric units, Btu can be a relatively intuitive unit because an exajoule is only 5 to 6 percent larger in energy content than a quadrillion Btu.

Emissions data are reported in metric units. This report uses the familiar “million metric tons” common in European industry instead of “gigagram,” which is equal to 1,000 metric tons and is the term favored by the scientific community. Metric tons are also relatively intuitive for users of English units, because a metric ton is only about 10 percent heavier than an English short ton.

Emissions of most greenhouse gases are reported here in terms of the full molecular weight of the gas (as in Table ES1). In Table ES2, however, and subsequently throughout the report, carbon dioxide is reported in carbon units, defined as the weight of the carbon content of carbon dioxide (i.e., just the “C” in CO<sub>2</sub>). Carbon dioxide units at full molecular weight can be converted into carbon units by dividing by 44/12, or 3.6667. This approach has been adopted for two reasons:

- Carbon dioxide is most commonly measured in carbon units in the scientific community. Scientists

argue that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide. Because combustion is never perfect, some portion of the emissions consists of carbon monoxide, methane, other volatile organic compounds, and particulates. These other gases (particularly carbon monoxide) eventually decay into carbon dioxide, but it is not strictly accurate to talk about “tons of carbon dioxide” emitted.

- Carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration. Because most fossil fuels are 75 percent to 90 percent carbon by weight, it is easy and convenient to compare the weight of carbon emissions (in carbon units) with the weight of the fuel burned. Similarly, carbon sequestration in forests and soils is always measured in tons of carbon, and the use of carbon units makes it simple to compare sequestration with emissions.

While carbon dioxide emissions can be measured in tons of carbon, emissions of other gases (such as methane) can also be measured in “carbon dioxide equivalent” units by multiplying their emissions (in metric tons) by their global warming potentials (GWPs). GWPs are discussed later in this chapter and delineated in Table 3. For comparability, carbon dioxide equivalent units can be converted to “carbon equivalent” by multiplying by 12/44 (as in Table ES2) to provide a measure of the relative effects of various gases on climate.

human impact on climate from normal temporal and spatial variations in temperature on a global scale. The most recent report of the IPCC, an international assemblage of scientists commissioned by the United Nations to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change, estimates that the global average surface temperature has increased by  $0.6^{\circ} \pm 0.2^{\circ}\text{C}$  since the late 19th century<sup>3</sup> (see box on page 4). The IPCC goes on to conclude that: "There is new and stronger evidence that most of the warming observed

over the last 50 years is attributable to human activities."<sup>4</sup>

In the aftermath of the IPCC report, the Bush Administration, in May 2001, as part of its review of U.S. policy on climate change, requested that the National Academy of Sciences identify areas of uncertainty in the science of climate change, as well as review the IPCC report and summaries. The National Academy of Sciences commissioned the National Research Council to carry out this review. The National Research Council in

## What's New in This Report

### All Chapters

- The Intergovernmental Panel on Climate Change (IPCC) has updated a number of the 100-year greenhouse gas global warming potential (GWP) coefficients,<sup>a</sup> including methane (increased from 21 to 23), nitrous oxide (decreased from 310 to 296), sulfur hexafluoride (decreased from 23,900 to 22,200), and perfluoromethane (decreased from 6,500 to 5,700) that were reported in an earlier IPCC report.<sup>b</sup> The greenhouse gas emissions estimates in this report are based on the new IPCC-updated GWPs (see box on page 12 for a comparison of U.S. emissions calculated with the earlier and revised GWPs).

### Chapter 1

- In keeping with the *1996 Revised IPCC Guidelines for the Preparation of National Inventories* and an IPCC Expert Working Group Meeting on Good Practices in Inventory Preparation held in the United Kingdom in October 1999, a study of the uncertainty in greenhouse gas emissions data was conducted using Monte Carlo simulations. This analysis supplements the results presented in last year's report for a study of uncertainty strictly in energy-related carbon dioxide emissions. A summary of the current results is included in Chapter 1.

### Chapter 2

- In this year's report, carbon dioxide emissions attributed to nonutility power producers have been removed from the industrial sector and placed in a combined electric power sector, where they have been shared out to end-use sectors in

proportion to the amount of electricity purchased by each sector.

- In 1998, EIA conducted a Manufacturing Energy Consumption Survey. The results of the 1998 survey have been used to calculate emissions from the manufacturing subsector, which makes up 85 percent of the U.S. industrial sector.

### Chapter 5

- The data presented in Chapter 5 for HFCs, PFCs, SF<sub>6</sub>, and other gases are provided by the U.S. Environmental Protection Agency (EPA). This year, the EPA updated a number of its methodologies in order to improve the accuracy and comprehensiveness of the emissions estimates. The Voluntary SF<sub>6</sub> Emissions Reduction Partnership, launched by the EPA in 1999, provided new information on SF<sub>6</sub> emissions from electric power systems and the magnesium industry. In addition, PFC emissions estimates have been revised on the basis of new data from the EPA's Voluntary Aluminum Industrial Partnership Program and from its Global Programs Division, which have resulted in revised emission factors for emissions from aluminum production. The EPA revised the methodology for estimating emissions from semiconductor manufacturing to include production data for 1990-1994 and data reported directly by semiconductor manufacturers for other years. For the substitution of ozone-depleting substances, revisions to chemical substitution trends and new information from industry representatives have led to revised assumptions for the EPA Vintaging Model.

<sup>a</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 388-390.

<sup>b</sup>Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

<sup>3</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 26.

<sup>4</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 10.

### Key Findings from the Third Assessment Report by the Intergovernmental Panel on Climate Change

The IPCC is an international assemblage of scientists commissioned by the United Nations to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change. The Third Assessment Report by the IPCC, published in 2001, includes the following key findings:

- **The global average surface temperature has increased over the 20th century by about 0.6°C.**
  - The global average surface temperature (the average of near-surface air temperature over land and sea surface temperature) has increased since 1861. Over the 20th century the increase has been  $0.6 \pm 0.2^\circ\text{C}$ .
- **Temperatures have risen during the past four decades in the lowest 8 kilometers of the atmosphere.**
  - Since the late 1950s (the period of adequate observations from weather balloons), the overall global temperature increases in the lowest 8 kilometers of the atmosphere and in surface temperature have been similar at  $0.1^\circ\text{C}$  per decade.
- **Snow cover and ice extent have decreased.**
  - Satellite data show that there are very likely to have been decreases of about 10 percent in the extent of snow cover since the late 1960s, and ground-based observations show that there is very likely to have been a reduction of about 2 weeks in the annual duration of lake and river ice cover in the mid- and high latitudes of the Northern Hemisphere over the 20th century.
- **Global average sea level has risen and ocean heat content has increased.**
  - Tide gauge data show that global average sea level rose by between 0.1 and 0.2 meters during the 20th century. Global ocean heat content has increased since the late 1950s, the period for which adequate observations of subsurface ocean temperatures have been available.
- **Concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities.**
  - The atmospheric concentration of carbon dioxide ( $\text{CO}_2$ ) has increased by 31 percent since 1750. The present  $\text{CO}_2$  concentration has not been exceeded during the past 420,000 years and probably not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years.
  - The atmospheric concentration of methane ( $\text{CH}_4$ ) has increased by 1,060 parts per billion (151 percent) since 1750 and continues to increase. The present  $\text{CH}_4$  concentration has not been exceeded during the past 420,000 years.
  - The atmospheric concentration of nitrous oxide ( $\text{N}_2\text{O}$ ) has increased by 46 parts per billion (17 percent) since 1750 and continues to increase. The present  $\text{N}_2\text{O}$  concentration has not been exceeded during at least the past 1,000 years.
  - Since 1995, the atmospheric concentrations of many of those halocarbon gases that are both ozone-depleting and greenhouse gases (e.g.,  $\text{CFCl}_3$  and  $\text{CF}_2\text{Cl}_2$ ) are either increasing more slowly or decreasing, both in response to reduced emissions under the regulations of the Montreal Protocol and its amendments. Their substitute compounds (e.g.,  $\text{CHF}_2\text{Cl}$  and  $\text{CF}_3\text{CH}_2\text{F}$ ) and some other synthetic compounds (e.g., perfluorocarbons [PFCs] and sulfur hexafluoride [ $\text{SF}_6$ ]) are also greenhouse gases, and their concentrations are currently increasing.
  - The radiative forcing due to increases of the well-mixed greenhouse gases from 1750 to 2000 is estimated to be 2.43 watts per square meter: 1.46 watts per square meter from  $\text{CO}_2$ ; 0.48 watts per square meter from  $\text{CH}_4$ ; 0.34 watts per square meter from the halocarbons; and 0.15 watts per square meter from  $\text{N}_2\text{O}$ .
- **Natural factors have made small contributions to radiative forcing over the past century.**
  - The radiative forcing due to changes in solar irradiance for the period since 1750 is estimated to be about +0.3 watts per square meter, most of which occurred during the first half of the 20th century. Since the late 1970s, satellite instruments have observed small oscillations due to the 11-year solar cycle. Mechanisms for the amplification of solar effects on climate have been proposed but currently lack a rigorous theoretical or observational basis.
  - Stratospheric aerosols from explosive volcanic eruptions lead to negative forcing, which lasts a few years. Several major eruptions occurred in the periods 1880 to 1920 and 1960 to 1991. The combined change in radiative forcing of the two major natural factors (solar variation and volcanic aerosols) is estimated to be negative for the past two, and possibly the past four, decades.

*(continued on page 5)*



### Key Findings from the Third Assessment Report by the Intergovernmental Panel on Climate Change (Continued)

- **There is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities.**
  - The warming over the past 50 years due to anthropogenic greenhouse gases can be identified despite uncertainties in forcing due to anthropogenic sulfate aerosol and natural factors (volcanos and solar irradiance).
- **Human influences will continue to change atmospheric composition throughout the 21st century.**
  - For the IPCC Special Report on Emission Scenarios (SRES) illustrative scenarios, relative to the year 2000, the global mean radiative forcing due to greenhouse gases continues to increase through the 21st century, with the fraction due to CO<sub>2</sub> projected to increase from slightly more than one-half to about three-quarters.
- **Global average temperature and sea level are projected to rise under all IPCC SRES scenarios.**
  - The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100. These results are for the full range of 35 SRES scenarios, based on a number of climate models.
  - Global mean sea level is projected to rise by 0.09 to 0.88 meters between 1990 and 2100, for the full range of SRES scenarios.
- **Anthropogenic climate change will persist for many centuries.**
  - Emissions of long-lived greenhouse gases (i.e., CO<sub>2</sub>, N<sub>2</sub>O, PFCs, and SF<sub>6</sub>) have a lasting effect on atmospheric composition, radiative forcing, and climate. For example, several centuries after CO<sub>2</sub> emissions occur, about one-quarter of the increase in CO<sub>2</sub> concentration caused by these emissions is still present in the atmosphere.
  - After greenhouse gas concentrations have stabilized, global average surface temperatures would rise at a rate of only a few tenths of a degree per century rather than several degrees per century as projected for the 21st century without stabilization.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001).

issuing its findings appeared to agree with some of the IPCC conclusions, but also seemed to suggest that further work needs to be done in identifying the impacts of natural climatic variability and reducing the uncertainty inherent in climate change modeling. Among the National Research Council findings are the following:<sup>5</sup>

*Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising. The changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability.*

*Because there is considerable uncertainty in current understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases and aerosols, current estimates of the magnitude of future warming should be regarded as tentative and subject to future adjustments (either upward or downward).*

*The committee generally agrees with the assessment of human-caused climate change presented in the IPCC Working Group I (WGI) scientific report, but seeks here to articulate more clearly the level of confidence that can be ascribed to those assessments and the caveats that need to be attached to them.*

While both the extent and consequences of human-induced global climate change remain uncertain, the threat of climate change has put in motion an array of efforts by the United States and other governments to find some mechanism for limiting the risk of climate change and ameliorating possible consequences. To date, efforts have focused on identifying levels and sources of emissions of greenhouse gases and on possible mechanisms for reducing emissions or increasing sequestration of greenhouse gases.

### Global Sources of Greenhouse Gases

Most greenhouse gases have both natural and human-made emission sources. There are, however, significant

<sup>5</sup>National Research Council, *Climate Change Science, An Analysis of Some Key Questions* (Washington, DC: National Academy Press 2001), p. 1.

natural mechanisms (land-based or ocean-based sinks) for removing them from the atmosphere. However, increased levels of anthropogenic (human-made) emissions have pushed the total level of greenhouse gas emissions (both natural and anthropogenic) above the natural absorption rates for these gases. This positive imbalance between emissions and absorption has resulted in the continuing growth in atmospheric concentrations of these gases. Table 2 illustrates the relationship between anthropogenic (human-made) and natural emissions and absorption of the principal greenhouse gases.

**Water Vapor.** Water vapor, as noted above, is the most common greenhouse gas present in the atmosphere. It is emitted into the atmosphere in enormous volumes through natural evaporation from oceans, lakes, and soils and is returned to Earth in the form of rain and snow. As a natural emission generally beyond human control, water vapor has not been included in climate change options under the United Nations Framework Convention on Climate Change. The recent IPCC report, however, cites a possible positive feedback from increased water vapor formation due to increased warming caused by increased atmospheric CO<sub>2</sub> concentrations.<sup>6</sup> Increased atmospheric temperatures increase the water-holding capability of the atmosphere. According to some of the IPCC emission scenarios, increased

water vapor content could double the predicted atmospheric warming above what it would be if water vapor concentration stayed constant. These scenarios, however, have an element of uncertainty due to the possible countervailing effect of increased cloud formation, which can act to cool the planet by absorbing and reflecting solar radiation or warm the planet through the emission of long-wave radiation. According to the IPCC, increases in atmospheric temperatures would not necessarily result in increased concentrations of water vapor, because most of the atmosphere today is undersaturated.

**Carbon Dioxide.** Carbon is a common element on the planet, and immense quantities can be found in the atmosphere, in soils, in carbonate rocks, and dissolved in ocean water. All life on Earth participates in the “carbon cycle,” by which carbon dioxide is extracted from the air by plants and decomposed into carbon and oxygen, with the carbon being incorporated into plant biomass and the oxygen released to the atmosphere. Plant biomass, in turn, ultimately decays (oxidizes), releasing carbon dioxide back into the atmosphere or storing organic carbon in soil or rock. There are vast exchanges of carbon dioxide between the ocean and the atmosphere, with the ocean absorbing carbon from the atmosphere and plant life in the ocean absorbing carbon from water, dying, and spreading organic carbon on the sea

**Table 2. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases**

Gas	Sources			Absorption	Annual Increase in Gas in the Atmosphere
	Natural	Human-Made	Total		
Carbon Dioxide (Million Metric Tons Carbon Equivalent) <sup>a</sup> . . . . .	210,000	6,300	216,300	213,100	3,200
Methane (Million Metric Tons of Gas) <sup>b</sup> . . . . .	239	359	598	576	22
Nitrous Oxide (Million Metric Tons of Gas) <sup>c</sup> . . . . .	9.5	6.9	16.4	12.6	3.8

<sup>a</sup>Carbon dioxide natural source and absorption of 210,000 million metric tons carbon equivalent, based on balanced flux of 120,000 million metric tons carbon equivalent between land and atmosphere and 90,000 million metric tons carbon equivalent between oceans and atmosphere, from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Figure 3.1, p. 188. Human-made emissions of 6,300 million metric tons carbon equivalent and distribution of those emissions (atmospheric absorption 3,200 million metric tons carbon equivalent, ocean absorption 1,700 million metric tons carbon equivalent, and land absorption 1,400 million metric tons carbon equivalent), taken from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 39.

<sup>b</sup>Methane total sources, absorption, and annual atmospheric increases from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250. Distinction between natural and human-made sources based on the assumption that 60 percent of total sources are anthropogenic, from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 248.

<sup>c</sup>Nitrous oxide total and human-made sources, absorption, and atmospheric increases from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.4, p. 252. Nitrous oxide natural sources (9.5 million metric tons of gas) derived by subtracting human-made sources from total sources.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

<sup>6</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 49.

bottom, where it is eventually incorporated into carbonate rocks such as limestone.

Records from Antarctic ice cores indicate that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide to the atmosphere exceeding absorption. Consequently, carbon dioxide concentrations in the atmosphere have been steadily rising. According to the IPCC, before 1750, atmospheric carbon dioxide concentration was around  $280 \pm 10$  parts per million for several thousand years. The IPCC goes on to say that the present carbon dioxide concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years.<sup>7</sup>

The most important natural sources of carbon dioxide are releases from the oceans (90 billion metric tons carbon equivalent per year) and land (120 billion metric tons carbon equivalent annually), including 60 billion metric tons carbon equivalent from plant respiration, 55 billion metric tons carbon equivalent from non-plant respiration (bacteria, fungi, and herbivores) and 4 billion metric tons carbon equivalent from combustion of natural and human-made fires.<sup>8</sup> Known anthropogenic sources (including deforestation) were estimated to account for about 7.9 billion metric tons of carbon per year during the 1989 to 1998 time period.<sup>9</sup> The principal anthropogenic source is the combustion of fossil fuels, which accounts for about 80 percent of total anthropogenic emissions of carbon worldwide. Natural processes—primarily, uptake by the ocean and photosynthesis—absorb substantially all the naturally produced carbon dioxide and some of the anthropogenic carbon dioxide, leading to an annual net increase in carbon dioxide in the atmosphere of 3.1 to 3.3 billion metric tons.<sup>10</sup>

**Methane.** Methane is also a common compound. The methane cycle is less well understood than the carbon cycle. Natural methane is released primarily by anaerobic decay of vegetation in wetlands, by the digestive tracts of termites in the tropics, by the ocean, and by leakage from methane hydrate deposits. The principal anthropogenic sources are leakages from the production

of fossil fuels, human-promoted anaerobic decay in landfills, and the digestive processes of domestic animals. Anthropogenic sources are estimated to be 60 percent of total methane emissions.<sup>11</sup> The main sources of absorption are thought to be tropospheric reactions with hydroxyl(OH) radicals that break down methane into  $\text{CH}_3$  and water vapor (506 million metric tons), stratospheric reactions with hydroxyl radicals and chlorine (40 million metric tons), and decomposition by bacteria in soils (30 million metric tons). Known and unknown sources of methane are estimated to total 598 million metric tons annually; known sinks (i.e., absorption by natural processes) total about 576 million metric tons. The annual increase in methane concentration in the atmosphere accounts for the difference of 22 million metric tons.<sup>12</sup>

**Nitrous Oxide.** The sources and absorption of nitrous oxide are much more speculative than those for other greenhouse gases. The principal natural sources are thought to be bacterial breakdown of nitrogen compounds in soils, particularly forest soils, fluxes from ocean upwellings, and stratospheric photo dissociation and reaction with electronically excited oxygen atoms. The primary human-made sources are enhancement of natural processes through application of nitrogen fertilizers, combustion of fuels (in fossil-fueled power plants and from the catalytic converters in automobiles), certain industrial processes (nylon and nitric acid production), biomass burning, and cattle and feedlots. Worldwide, estimated known sources of nitrous oxide total 16.4 million metric tons annually (6.9 million metric tons from anthropogenic sources), and known sinks total 12.6 million metric tons. The annual increase in concentrations in the atmosphere is thought to total 3.8 million metric tons.<sup>13</sup>

**Halocarbons and Other Gases.** During the 20th century, human ingenuity created an array of “engineered” chemicals, not normally found in nature, whose special characteristics render them particularly useful. A particular family of engineered gases is the halocarbons. A halocarbon is a compound containing either chlorine, bromine, or fluorine and carbon. Halocarbons are powerful greenhouse gases. Halocarbons that contain

<sup>7</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 185.

<sup>8</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 188, 191.

<sup>9</sup>Intergovernmental Panel on Climate Change, *Land Use, Land-Use Change, and Forestry. A Special Report to the IPCC* (Cambridge, UK: Cambridge University Press, 2000).

<sup>10</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, (Cambridge, UK: Cambridge University Press, 2001), p. 208.

<sup>11</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, (Cambridge, UK: Cambridge University Press, 2001), p. 248.

<sup>12</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250.

<sup>13</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.4, p. 252.

bromine or chlorine also deplete the Earth's ozone layer. One of the best known groups of halocarbons is the chlorofluorocarbons (CFCs), particularly CFC-12, often known by its trade name, "Freon-12." CFCs have many desirable features: they are relatively simple to manufacture, inert, nontoxic, and nonflammable. Because CFCs are chemically stable, once emitted, they remain in the atmosphere for hundreds or thousands of years. Because they are not found in nature, these molecules absorb reflected infrared radiation at wavelengths that otherwise would be largely unabsorbed, and they are potent greenhouse gases, with a direct radiative forcing effect hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide.

Because of their long atmospheric lives, a portion of the CFCs emitted into the atmosphere eventually find their way into the stratosphere, where they can be destroyed by sunlight. This reaction, however, releases free chlorine atoms into the stratosphere, and the free chlorine atoms tend to combine with stratospheric ozone, which protects the surface of the Earth from certain wavelengths of potentially damaging solar ultraviolet radiation (ultraviolet radiation, for example, causes human and animal skin cancers).

The threat posed by CFCs to the ozone layer has caused the United States and many other countries to commit themselves to phasing out the production of CFCs and their chemical cousins, hydrochlorofluorocarbons (HCFCs), pursuant to an international treaty, the 1987 Montreal Protocol. As use of CFCs has declined, many related chemicals have emerged as alternatives, including HCFCs and hydrofluorocarbons (HFCs). HCFCs are similar to CFCs, but they are more reactive and consequently have shorter atmospheric lives, with less effect on the ozone layer and smaller direct global warming effects. HCFCs are also being phased out, but over a longer time scale. The ozone-depleting substances with the most potential to influence climate, CFC-11, CFC-12 and CFC-113, are beginning to show reduced growth rates in atmospheric concentrations in the aftermath of the Montreal Protocol. The present radiative forcing of CFC-11 is about 0.065 watts per square meter, and that of CFC-12 is around 0.2 watts per square meter.<sup>14</sup>

HFCs have no chlorine and consequently have no effect on the ozone layer, but they are powerful greenhouse gases. The three most prominent HFCs in the atmosphere today are HFC-23, HFC-134a, and HFC-152a.

HFC-23 is formed as a byproduct of HCFC-22 production, which is being phased out under the Montreal Protocol. Although HFC-23 is very long-lived (260 years), the growth rate in its atmospheric concentration has begun to level off in accordance with reductions in HCFC-22 production. HFC-134a production was rare before 1990, but in 1994 HFC-134a was adopted as the standard motor vehicle air conditioning refrigerant in virtually all new cars made in America. HFC-134a has a lifetime of 13.8 years, and emissions have grown rapidly from near zero in 1990 to 0.032 million metric tons in 1996.<sup>15</sup> HFC-152a emissions have risen steadily since about 1995, but its short lifetime of 1.4 years has kept concentration levels below 1 part per trillion.

Another new class of engineered halocarbons are the perfluorocarbons (PFCs), which include perfluoromethane ( $\text{CF}_4$ ) and perfluoroethane ( $\text{C}_2\text{F}_6$ ). PFCs are emitted as byproducts of aluminum smelting and are increasingly being used in the manufacture of semiconductors. They are powerful greenhouse gases and extremely long-lived. Perfluoromethane has 100-year global warming potential (GWP) of 5,700 and a lifetime in excess of 50,000 years. Perfluoroethane has a GWP of 11,900 and a lifetime of 10,000 years. Perfluoromethane is a naturally occurring compound in fluorites, and emissions from this source create a natural abundance of 40 parts per trillion in the atmosphere. Increases in anthropogenic emissions, growing at about 1.3 percent annually, have raised atmospheric concentrations to 80 parts per trillion.<sup>16</sup> Perfluoroethane does not occur naturally in the atmosphere and current concentrations (3.0 parts per trillion) are attributable to anthropogenic emissions, which are growing by 3.2 percent annually. Sinks for PFCs are photolysis and ion reactions in the mesosphere.

Sulfur hexafluoride ( $\text{SF}_6$ ) is used as an insulator in utility-scale electrical equipment and as a cover gas in magnesium smelting. It is not a halocarbon, but it is a powerful greenhouse gas.  $\text{SF}_6$  has a 100-year GWP of 22,200 and a lifetime of 3,200 years. Like perfluoromethane,  $\text{SF}_6$  occurs naturally in fluorites, which produce a natural abundance of 0.01 parts per trillion in the atmosphere. Current atmospheric concentrations (3.0 parts per trillion) can be traced to anthropogenic emissions, which grew by approximately 7 percent annually during the 1980s and 1990s. Also like PFCs, sinks for  $\text{SF}_6$  are photolysis and ion reactions in the mesosphere.<sup>17</sup>

<sup>14</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Figures 4.6 and 4.7, p. 255.

<sup>15</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

<sup>16</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

<sup>17</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.



There may be other chemicals not yet identified that exhibit radiative properties similar to those of the halocarbons and other gases described above. One recent discovery identified trifluoromethyl sulfur pentafluoride ( $\text{SF}_5\text{CF}_3$ ) as a new anthropogenic greenhouse gas in the atmosphere.<sup>18</sup> It is believed that  $\text{SF}_5\text{CF}_3$  is created by the breakdown of  $\text{SF}_6$  in high-voltage equipment, which produces  $\text{CF}_3$  that reacts with  $\text{SF}_5$  radicals resulting from high-voltage discharges. Its atmospheric concentration has grown from near zero in 1960 to 0.12 parts per trillion in 1999. To date,  $\text{SF}_5\text{CF}_3$  has the largest radiative forcing on a per-molecule basis of any gas found in the atmosphere.<sup>19</sup> This gas is not yet specifically addressed by the United Nations Framework Convention on Climate Change.

A number of chemical solvents are also strong greenhouse gases. The solvents carbon tetrachloride (GWP of 1,800 and lifetime of 35 years) and methyl chloroform (GWP of 140 and lifetime of 4.8 years), however, are regulated in the United States both as ozone depleters and for toxicity. All these gases have direct radiative forcing effects, which are offset to some degree by their ozone-depleting effects.

With the advent of the United Nations Framework Convention and the Kyoto Protocol, the halocarbon and other industrial chemicals can be grouped into two categories:

- Ozone-depleting chemicals regulated under the Montreal Protocol but excluded from the Framework Convention (CFCs, HCFCs, and others)
- “Kyoto gases” (HFCs, PFCs, and  $\text{SF}_6$ ).

The “Kyoto gases” are deemed to “count” for the purposes of meeting national obligations under the Framework Convention. The ozone depleters, however, are excluded from the Framework Convention because they are regulated by the Montreal Protocol.

**Other Important Radiative Gases.** There are a number of additional gases, resulting in part from human sources, that produce radiative forcing of the Earth’s climate but are not included under the Framework Convention or the Montreal Protocol. In general, these gases are short-lived, they have only indirect climate effects, or there is a fair amount of uncertainty about their climatic impacts. They can be broken down into three

general classes: (1) ozone, both tropospheric and stratospheric; (2) criteria pollutants that are indirect greenhouse gases; and (3) aerosols, including sulfates and black soot.

Ozone ( $\text{O}_3$ ) is present in both the troposphere and the stratosphere. Tropospheric ozone is not directly emitted into the atmosphere but instead forms via the photochemical reactions of various ozone precursors (primarily nitrogen oxides and volatile organic compounds). In the troposphere, ozone acts as a direct greenhouse gas. The lifetime of ozone in the atmosphere varies from weeks to months, which imparts an element of uncertainty in estimating tropospheric ozone’s radiative forcing effects. The IPCC estimates that the radiative forcing of tropospheric ozone is  $0.35 \pm 0.2$  watts per square meter.<sup>20</sup> The depletion of stratospheric ozone due to the emission of halocarbons, on the other hand, has tended to cool the planet. The IPCC estimates that the cooling due to stratospheric ozone depletion is on the order of  $-0.15 \pm 0.1$  watts per square meter.<sup>21</sup> As the ozone layer recovers, however, due to the impacts of the Montreal Protocol, it is expected that stratospheric ozone will exert a positive radiative forcing effect on the Earth’s climate.

There are also a number of compounds (carbon monoxide, nitrogen oxides, and volatile organic compounds) that are indirect greenhouse gases. These gases are regulated in the United States pursuant to the Clean Air Act, and they are often referred to as “criteria pollutants.” They are emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), and they influence climate indirectly through the formation of ozone and their effects on the lifetime of methane emissions in the atmosphere. Carbon monoxide, via its effects on hydroxyl radicals, can help promote the abundance of methane, a powerful greenhouse gas, in the atmosphere, as well as increase ozone formation. Some IPCC model calculations indicate that 100 metric tons of carbon monoxide emissions is equivalent to the emissions of about 5 metric tons of methane.<sup>22</sup>

Nitrogen oxides, including  $\text{NO}$  and  $\text{NO}_2$ , influence climate by their impacts on other greenhouse gases. Nitrogen oxides not only promote ozone formation, they also impact (negatively) methane and HFC concentrations in the atmosphere. The deposition of nitrogen oxides could

<sup>18</sup>W.T. Sturges et al., “A Potent Greenhouse Gas Identified in the Atmosphere:  $\text{SF}_5\text{CF}_3$ ,” *Science*, Vol. 289 (July 28, 2000), pp. 611-613.

<sup>19</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

<sup>20</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 43.

<sup>21</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 43.

<sup>22</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 44.

also reduce atmospheric carbon dioxide concentrations by fertilizing the biosphere.<sup>23</sup>

Volatile organic compounds (VOCs), although they have some short-lived direct radiative-forcing properties, primarily influence climate indirectly via their promotion of ozone formation and production of organic aerosols. The main sources of global VOC emissions are vegetation (primarily tropical) (377 million metric tons carbon equivalent), fossil fuels (161 million metric tons carbon equivalent), and biomass burning (33 million metric ton carbon equivalent).<sup>24</sup>

Aerosols, which are small airborne particles or droplets, also affect the Earth's climate. Aerosols have both direct effects, through their ability to absorb and scatter solar and thermal radiation, and indirect effects, through their ability to modify the physical properties and amount of clouds. In terms of climate change, the most prominent aerosols are sulfates, fossil fuel black carbon aerosols (sometimes called "black soot"), fossil fuel organic carbon aerosols, and biomass-burning aerosols.

One of the primary precursors of sulfates is sulfur dioxide (SO<sub>2</sub>), which is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds. The major source of anthropogenic black soot and organic carbon aerosols is the burning of fossil fuels, primarily coal and diesel fuels. Biomass-burning aerosols are formed by the incomplete combustion of forest products. The IPCC estimates the direct radiative forcing for aerosols as follows: sulfates, -0.4 watts per square meter; black soot, +0.2 watts per square meter; fossil fuel organic carbon, -0.1 watts per square meter; and biomass-burning aerosols, -0.2 watts per square meter.<sup>25</sup> Although the indirect climate effects of aerosols are uncertain, some preliminary evidence points to an indirect cooling effect due to cloud formation.<sup>26</sup>

## Relative Forcing Effects of Various Gases

The ability of a greenhouse gas to affect global temperatures depends not only on its radiative or heat-trapping properties but also on its lifetime or stability in the atmosphere. Because the radiative properties and lifetimes of greenhouse gases vary greatly, comparable increases in the concentrations of different greenhouse gases can have vastly different heat-trapping effects. For example, among the "Kyoto gases," carbon dioxide is the most prominent in terms of emissions, atmospheric concentration, and radiative forcing, but it is among the least effective as a greenhouse gas. Other compounds, on a gram-per-gram basis, appear to have much greater effects.

There has been extensive study of the relative effectiveness of various greenhouse gases in trapping the Earth's heat. Such research has led to the development of the concept of a "global warming potential," or GWP. The GWP is intended to illustrate the relative impacts on global warming of a given gas relative to carbon dioxide over a specific time horizon. Over the past decade, the IPCC has conducted an extensive research program aimed at summarizing the effects of various greenhouse gases through a set of GWPs. The results of that work were originally released in 1995 in an IPCC report, *Climate Change 1994*,<sup>27</sup> and subsequently updated in *Climate Change 1995*<sup>28</sup> and *Climate Change 2001*.<sup>29</sup>

The calculation of a GWP is based on the radiative efficiency (heat-absorbing ability) of the gas relative to the radiative efficiency of the reference gas (carbon dioxide), as well as the removal process (or decay rate) for the gas relative to the reference gas over a specified time horizon. The IPCC, however, has pointed out that there are elements of uncertainty in calculating GWPs.<sup>30</sup> The uncertainty takes several forms:

<sup>23</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 44.

<sup>24</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.7(a), p. 258.

<sup>25</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 45.

<sup>26</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 45.

<sup>27</sup>Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

<sup>28</sup>Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

<sup>29</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

<sup>30</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 385-386.

- The radiative efficiencies of greenhouse gases do not necessarily stay constant over time (as calculated in GWPs), particularly if the abundance of a gas in the atmosphere increases. Each gas absorbs radiation in a particular set of wavelengths, or “window,” in the spectrum. In some cases, where concentrations of the gas are low and no other gases block radiation in the same window, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, a larger and larger portion of the total light passing through the “window” will already have been captured, and the marginal effects of additional emissions will not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or carbon dioxide, tends to be less than that of a rare gas, such as sulfur hexafluoride. This “diminishing return” effect implies that increasing the concentration of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.
- The lifetime of a greenhouse gas (used in GWP calculations), particularly carbon dioxide, is also subject to uncertainty. Various natural processes cause many greenhouse gases to decompose into other gases or to be absorbed by the ocean or ground. These processes can be summarized in terms of the “atmospheric lifetime” of a particular gas, or the period of time it would take for natural processes to remove a unit of emissions from the atmosphere.

Some gases, such as CFCs, have very long atmospheric lifetimes, in the hundreds of years. Others, such as carbon monoxide, have lives measured in hours or days. Methane, which decays into carbon dioxide over a period of a few years, has a much larger short-run effect on global warming than does an equivalent amount of carbon dioxide; however, over longer and longer periods—from 10 years to 100 years to 500 years, for example—the differences between the GWPs of methane and carbon dioxide become less significant, because carbon dioxide has a longer atmospheric lifetime than methane.

Table 3 summarizes the consensus results of the most recent studies by scientists working on behalf of the IPCC, showing estimates of atmospheric lifetimes and global warming potentials across various time scales. For the purposes of calculating “CO<sub>2</sub> equivalent” units for this report, 100-year GWPs are used.

The GWPs discussed above are direct GWPs in that they consider only the direct impact of the emitted gas. The IPCC has also devoted effort to the study of indirect GWPs. Indirect GWPs are based on the climatic impacts of the atmospheric decomposition of a gas into other gases. A number of gases—including methane, carbon monoxide, halocarbons, and nitrogen oxides—are thought to have indirect climatic effects. Methane indirectly influences the climate through ozone formation and the production of carbon dioxide. Carbon monoxide can promote ozone formation and extend the lifetime of methane in the atmosphere, which results in a positive indirect GWP. Some halocarbons, such as CFCs and

**Table 3. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide**  
(Kilogram of Gas per Kilogram of Carbon Dioxide)

Gas	Lifetime (Years)	Direct Effect for Time Horizons of		
		20 Years	100 Years	500 Years
Carbon Dioxide . . . . .	5 – 200 <sup>a</sup>	1	1	1
Methane . . . . .	12	62	23	7
Nitrous Oxide . . . . .	114	275	296	156
HFCs, PFCs, and Sulfur Hexafluoride . . . . .				
HFC-23 . . . . .	260	9,400	12,000	10,000
HFC-125 . . . . .	29	5,900	3,400	1,100
HFC-134a . . . . .	13.8	3,300	1,300	400
HFC-152a . . . . .	1.4	410	120	37
HFC-227ea . . . . .	33	5,600	3,500	1,100
Perfluoromethane (CF <sub>4</sub> ) . . . . .	50,000	3,900	5,700	8,900
Perfluoroethane (C <sub>2</sub> F <sub>6</sub> ) . . . . .	10,000	8,000	11,900	18,000
Sulfur Hexafluoride (SF <sub>6</sub> ) . . . . .	3,200	15,100	22,200	32,400

<sup>a</sup>No single lifetime can be defined for carbon dioxide due to different rates of uptake by different removal processes.

Note: The typical uncertainty for global warming potentials is estimated by the Intergovernmental Panel on Climate Change at ±35 percent.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 388-389.

### Comparison of Global Warming Potentials from the IPCC's Second and Third Assessment Reports

Global warming potentials (GWPs) are used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative efficiency (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO<sub>2</sub>), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO<sub>2</sub>. The GWP provides a construct for converting emissions of various gases into a common measure, which allows climate analysts to aggregate the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon or carbon dioxide equivalents. The table at the right compares the GWPs published in the Second and Third Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC).

In compiling its greenhouse gas emission estimates, EIA attempts to employ the most current data sources. For that reason, and because the IPCC is generally considered the authoritative source for GWPs, the GWP values from the IPCC's Third Assessment Report are used in this report. It is important to point out, however, that countries reporting to the United Nations Framework Convention on Climate Change (UNFCCC), including the United States, have been compiling estimates based on the GWPs from the IPCC's Second Assessment Report. The UNFCCC Guidelines on Reporting and Review, adopted before the publication of the Third Assessment Report, require emission estimates to be based on the GWPs in the IPCC Second Assessment Report. This will probably continue in the short term, until the UNFCCC reporting rules are changed. The U.S. Environmental Protection Agency (EPA), which compiles the official U.S. emissions inventory for submission to the UNFCCC, intends to present estimates based on the GWPs published in the Second Assessment Report in

### Comparison of 100-Year GWP Estimates from the IPCC's Second (1996) and Third (2001) Assessment Reports

Gas	1996 IPCC GWP	2001 IPCC GWP
Methane.....	21	23
Nitrous Oxide.....	310	296
HFC-23.....	11,700	12,000
HFC-125.....	2,800	3,400
HFC-134a.....	1,300	1,300
HFC-143a.....	3,800	4,300
HFC-152a.....	140	120
HFC-227ea.....	2,900	3,500
HFC-236fa.....	6,300	9,400
Perfluoromethane (CF <sub>4</sub> )....	6,500	5,700
Perfluoroethane (C <sub>2</sub> F <sub>6</sub> )....	9,200	11,900
Sulfur Hexafluoride (SF <sub>6</sub> )....	23,900	22,200

its *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* for release in April 2002.

The table below shows 2000 U.S. carbon-equivalent greenhouse gas emissions calculated using the IPCC's 1996 and 2001 GWPs. The estimate for total U.S. emissions in 2000 is 0.7 percent higher when the revised GWPs are used. The estimates for earlier years generally follow the same pattern. Using the 2001 GWPs, estimates of carbon-equivalent methane emissions are 9.5 percent higher, and carbon-equivalent nitrous oxide emissions are 4.5 percent lower. Carbon-equivalent emissions of HFCs, PFCs, and SF<sub>6</sub> are lower for some years and higher for others, depending on the relative shares of the three gases.

Gas	IPCC GWP		Annual GWP-Weighted Emissions								
			1990			1999			2000		
	1996	2001	1996 GWP	2001 GWP	Percent Change	1996 GWP	2001 GWP	Percent Change	1996 GWP	2001 GWP	Percent Change
Carbon Dioxide.....	1	1	1,355	1,355	0.0	1,536	1,536	0.0	1,583	1,583	0.0
Methane.....	21	23	181	199	9.5	164	180	9.5	161	177	9.5
Nitrous Oxide.....	310	296	99	94	-4.5	105	100	-4.5	104	99	-4.5
HFCs, PFCs, and SF <sub>6</sub> ...	—	—	31	30	-2.4	44	45	2.9	45	47	3.5
<b>Total.....</b>	—	—	<b>1,666</b>	<b>1,678</b>	<b>0.6</b>	<b>1,848</b>	<b>1,860</b>	<b>0.6</b>	<b>1,894</b>	<b>1,906</b>	<b>0.7</b>



HCFCs, produce an indirect cooling effect by removing ozone from the stratosphere. The indirect cooling effect leads to lower net GWPs in a number of cases, but in most cases their net GWPs are still positive. Nitrogen oxides promote the formation of tropospheric ozone and, thus, have a positive indirect GWP—on the order of 5 for surface emissions and 450 for aircraft emissions.<sup>31</sup>

## International Developments in Global Climate Change

Rising concentrations of carbon dioxide in the atmosphere were first detected in the late 1950s, and observations of atmospheric concentrations of methane, nitrous oxide, and other gases began in the late 1970s. Concern about the effects of rising atmospheric concentrations of greenhouse gases remained largely the province of atmospheric scientists and climatologists, however, until the mid-1980s, when a series of international scientific workshops and conferences began to move the topic onto the agenda of United Nations specialized agencies, particularly, the World Meteorological Organization (WMO).

The IPCC was established under the auspices of the United Nations Environment Program and the WMO in late 1988, to accumulate available scientific research on climate change and to provide scientific advice to policymakers. A series of international conferences provided impetus for an international treaty aimed at limiting the human impact on climate. In December 1990, the United Nations established the Intergovernmental Negotiating Committee (INC) for a Framework Convention on Climate Change. Beginning in 1991, the INC hosted a series of negotiating sessions that culminated in the adoption, by more than 160 countries, including the United States, of the Framework Convention on Climate Change (FCCC), opened for signature at the “Earth Summit” in Rio de Janeiro, Brazil, on June 4, 1992.<sup>32</sup>

### From the Framework Convention to the Kyoto Protocol

The objective of the Framework Convention is stated as follows:

*The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.<sup>33</sup>*

The Framework Convention divided its signatories into two groups: the countries listed in Annex I to the Protocol, and all others. The Annex I countries include the 24 original members of the Organization for Economic Cooperation and Development (OECD) (including the United States), the European Union, and 14 countries with economies in transition (Russia, Ukraine, and Eastern Europe).<sup>34</sup>

The Convention requires all parties to undertake “policies and measures” to limit emissions of greenhouse gases, and to provide national inventories of emissions of greenhouse gases (Article 4.1a and b). Annex I parties are further required to take actions “with the aim of returning . . . to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases” (Article 4.2a and b). The signatories subsequently agreed that Annex I parties should provide annual inventories of greenhouse gas emissions.

In April 1993, President Clinton committed to stabilizing U.S. emissions of greenhouse gases at the 1990 level by 2000, using an array of voluntary measures. In the following years, however, greenhouse gas emissions in the United States and many other Annex I countries continued to increase. The climate negotiators, continuing to meet as “the Conference of the Parties [to the Framework Convention]” (COP), took up the question of how to limit emissions in the post-2000 period, a topic on which the Framework Convention was silent. In 1995, COP-1, held in Berlin, Germany, agreed to begin negotiating a post-2000 regime. In 1996, COP-2, held in Geneva, Switzerland, agreed that the regime would encompass binding limitations on emissions for the parties, to be signed at COP-3, which was to be held in Kyoto, Japan, in December 1997.

<sup>31</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 387-390.

<sup>32</sup>The Framework Convention was “adopted” by a vote of the conference of the parties on May 9th, while the signatures and ratifications of member states flowed in over a period of years. The treaty “entered into force” in 1994. There is a discussion of the development of the Convention in D. Bodanzky, “Prologue to the Climate Convention,” in I. Mintzer and J.A. Leonard (eds.), *Negotiating Climate Change: The Inside Story of the Rio Convention* (Cambridge, UK: Cambridge University Press, 1994), pp. 49-66.

<sup>33</sup>The official text of the Framework Convention can be found at web site [www.unfccc.de/index.html](http://www.unfccc.de/index.html).

<sup>34</sup>The Annex I nations include Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, European Union, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States of America. Belarus initially participated in the Framework Convention but did not join the Kyoto Protocol. Turkey initially joined the Convention but subsequently asked to withdraw from Annex I status and did not join the Kyoto Protocol. In June 1999, Kazakhstan applied for Annex I status but subsequently withdrew its application in June 2000.

### The Kyoto Protocol

The most fundamental feature of the Kyoto Protocol to the Framework Convention, adopted on December 11, 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries, which collectively are about 5 percent lower than the 1990 emissions of those countries taken as a group.<sup>35</sup> Developing country signatories do not have quantified targets. Some of the key features of the Protocol are summarized below:

- **Differentiated Targets.** Each Annex I signatory has a “quantified emissions reduction limitation commitment,” which limits the signatory to some fraction, ranging from 90 to 110 percent, of its 1990 greenhouse gas emissions.<sup>36</sup> Both the European Union (EU) and the individual members of the EU signed the Protocol and are responsible for meeting their commitments.
- **Commitment Period.** Each target is defined as the average of the signatory’s emissions over the 5-year period 2008-2012, called “the commitment period.”
- **Six Gases.** Participants are to limit their emissions of carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride, weighted by the GWP of each gas. HFCs and PFCs are actually classes of gases with multiple members, but the term “six gases” has stuck. Participants may use 1995 as the baseline for HFCs, PFCs, and sulfur hexafluoride, instead of 1990.
- **Demonstrable Progress.** Annex I countries are required to have made “demonstrable progress” toward achieving their commitments by 2005.
- **Land Use and Forestry.** The Protocol includes complicated provisions on forestry, the implication being that some emissions and sequestration arising from changes in land use and forestry since 1990 can be counted against the target.
- **Flexibility Mechanisms.** The Protocol includes an array of methods by which Annex I countries can spread and reduce the cost of emissions limitations. The flexibility mechanisms include:
  - **Emissions Trading.** Annex I countries can transfer portions of their quotas to one another.

- **Joint Implementation.** Annex I countries can undertake emissions reduction projects in other Annex I countries and receive a negotiated share of the emissions reductions generated by the projects.
- **Joint Fulfillment.** Like-minded Annex I countries (such as the EU) may band together to reallocate national targets within the group, so long as the collective target is met.
- **Clean Development Mechanism.** Annex I countries may undertake emissions reduction projects in non-Annex I countries and receive credits countable against national targets.
- **Entry into Force.** The Protocol enters into force when 55 countries *and* Annex I signatories with carbon dioxide emissions totaling 55 percent of total Annex I emissions “have deposited their instruments of ratification, acceptance, approval, or accession.” As of September 28, 2001, 84 countries (including 36 Annex I countries) had signed (not ratified) the Protocol. To date, 40 countries, including a number of Central and South American nations, several small island states, and some Central Asia nations, have ratified the Protocol. Only one Annex I country, Romania, has ratified the Protocol.<sup>37</sup>

### The Kyoto Protocol and the United States

The U.S. Government formally signed the Kyoto Protocol on November 12, 1998. Under the U.S. Constitution, however, the Government may adhere to treaties only with the “advice and consent” of the Senate.<sup>38</sup> In 2001, President Bush indicated that he does not intend to submit the Protocol to the Senate for ratification and that the United States will not agree to the Kyoto Protocol because “it exempts 80 percent of the world, including major population centers such as China and India, from compliance, and would cause serious harm to the U.S. economy.”<sup>39</sup> The United States, instead, plans to develop a National Climate Change Technology Initiative that would develop innovative, long-term technologies to address the issue of climate change.<sup>40</sup>

### Beyond the Kyoto Protocol

Since the signing of the Kyoto Protocol, the signatories have continued to shape the “work in progress.” At the

<sup>35</sup>The text of the Kyoto Protocol can also be found at web site [www.unfccc.de/index.html](http://www.unfccc.de/index.html).

<sup>36</sup>Several Eastern European states have been permitted to use emissions from the late 1980s, rather than 1990, as their baseline. All signatories may elect to use 1995 emissions of HFCs, PFCs, and sulfur hexafluoride as the baseline rather than 1990 emissions.

<sup>37</sup>See web site [www.unfccc.int/resource/kpstats.pdf](http://www.unfccc.int/resource/kpstats.pdf).

<sup>38</sup>Article II, Section 2, of the Constitution reads, in part: “He [the President] shall have power, by and with the advice and consent of the Senate, to make treaties, provided two thirds of the Senators present concur . . . .”

<sup>39</sup>Letter from President Bush To Senators Hagel, Helms, Craig, and Roberts, Office of the Press Secretary, The White House (March 13, 2001).

<sup>40</sup>Remarks by President Bush on Global Climate Change, Office of the Press Secretary, The White House (June 11, 2001).

fourth session of the Conference of the Parties (COP-4) in Buenos Aires, Argentina, in November 1998, a plan of action was adopted to finalize a number of the implementation issues of the Protocol. Negotiations at the fifth Conference of the Parties (COP-5) in Bonn, Germany, from October 25 through November 5, 1999, focused on developing rules and guidelines for emissions trading, joint implementation, and a Clean Development Mechanism (CDM), negotiating the definition and use of forestry activities and additional sinks, and understanding the basics of a compliance system, with an effort to complete this work at the sixth Conference of the Parties (COP-6) at The Hague, Netherlands, in November 2000.

The major goals of the COP-6 negotiations were to develop the concepts in the Protocol in sufficient detail that the Protocol could be ratified by enough Annex I countries to be put into force, and to encourage significant action by the non-Annex I countries to meet the objectives of the Framework Convention.<sup>41</sup> The COP-6 negotiations focused on a range of technical issues, including emissions reporting and review, communications by non-Annex I countries, technology transfer, and assessments of capacity needs for developing countries and countries with economies in transition.

The COP-6 negotiations were suspended in November 2000 without agreement on a number of issues, including the appropriate amount of credit for carbon sinks, such as forests and farmlands, and the use of flexible mechanisms, such as international emissions trading and the CDM, to reduce the cost of meeting the global emissions targets.<sup>42</sup> COP-6 was rescheduled to resume in the Spring/Summer of 2001 in Bonn, Germany.<sup>43</sup>

The COP-6 negotiations resumed in Bonn, Germany, on July 16, 2001 (COP-6 Part 2), again to focus on developing the concepts in the Protocol in sufficient detail that it could be ratified by enough Annex I countries to be put

into force. On July 23, 2001, 178 members/nations of the United Nations Framework Convention on Climate Change reached an agreement (the "Bonn Agreement") on the operational rulebook for the Kyoto Protocol.

The "Bonn Agreement" creates a Special Climate Change Fund and a Protocol Adaptation Fund to help developing countries adapt to climate change impacts, obtain clean technologies, and limit the growth in their emissions; allows developed nations to use carbon sinks to comply, in part, with their Kyoto Protocol emission reduction commitments; and establishes rules for the CDM, emissions trading, and Joint Implementation projects. The Bonn Agreement also emphasizes that domestic actions shall constitute a significant element of emission reduction efforts made by each Party and, also, establishes a Compliance Committee with a facilitative branch and an enforcement branch. In terms of compliance, for every ton of gas that a country emits over its target, it will be required to reduce an additional 1.3 tons during the Protocol's second commitment period, which starts in 2013.

The Bonn Agreement will be forwarded for official adoption at the Seventh Session of the Conference of the Parties (COP-7), which is to be held in Marrakech, Morocco, from October 29 to November 9, 2001. COP-7 is intended to set up the institutions necessary to make the Bonn Agreement and the Kyoto Protocol operational once ratification is achieved.

The Bush Administration has indicated that it has no objection to the participation of other countries in the Kyoto Protocol or the Bonn Agreement, even without U.S. participation. The Administration has indicated that it intends to develop U.S. alternatives to the Kyoto Protocol, including the National Climate Change Technology Initiative.<sup>44</sup>

<sup>41</sup>See U.N. Framework Convention on Climate Change, web site <http://cop6.unfccc.int/media/press.html>.

<sup>42</sup>"U.N. Conference Fails to Reach Accord on Global Warming," *New York Times* (November 26, 2000).

<sup>43</sup>"Odd Culprits in Collapse of Climate Talks," *New York Times* (November 28, 2000).

<sup>44</sup>Remarks by President Bush on Global Climate Change, Office of the Press Secretary, The White House (June 11, 2001).

## Analysis of Uncertainty in Greenhouse Gas Emissions

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, as established at the UNFCCC 4th Conference of the Parties in Kyoto, Japan in December 1997, recommend that nations carry out analyses to estimate the uncertainty in their national greenhouse gas emissions inventories. According to the guidelines, nations should construct 95 percent confidence intervals for their greenhouse gas emission estimates using classical sampling techniques, Monte Carlo techniques, or assessments by national experts. The United Nations Framework Convention on Climate Change (UNFCCC) subsequently requested that the IPCC complete its work on uncertainty and prepare a report on good practice in inventory management. In 2000, the IPCC issued its report establishing Tier 1 and Tier 2 methods of estimating uncertainty in greenhouse gas inventories as follows:<sup>a</sup>

- **Tier 1:** Estimation of uncertainties by source category using error propagation equations . . . and simple combination of uncertainties by source category to estimate overall uncertainty for one year and the uncertainty in the trend.
- **Tier 2:** Estimation of uncertainties by source category using Monte Carlo analysis, followed by the use of Monte Carlo techniques to estimate overall uncertainty for one year and the uncertainty in the trend.

In response to the IPCC's good practices guidelines, EIA in 1998 carried out a Tier 1 uncertainty analysis of U.S. greenhouse gas emissions for carbon dioxide, methane, nitrous oxide, and other gases. The results of that analysis can be found in Appendix C of this report. The Tier 1 approach, however, as pointed out by the IPCC may be inappropriate when combining non-normal distributions, as may be the case with some of the distributions for emissions factors and activities.

EIA recently undertook a Tier 2 uncertainty analysis of U.S. carbon dioxide, methane, and nitrous oxide emission estimates to augment its previous Tier 1 uncertainty analysis. The Tier 2 uncertainty analysis involves Monte Carlo simulations that facilitate the combination of various types of probability density functions. Through repeated iterations, points inside the relevant probability density functions for both the activity data and the emissions factors are sampled.

In order to carry out a Monte Carlo analysis, estimates of minimum, maximum, and random bias in emission factors and activity data must be established. The table on pages 17 and 18 shows the estimated bias and random uncertainties in activity data and emissions factors for carbon dioxide, methane, and nitrous oxide, delineated by fuel type and activity, that was used in the Monte Carlo analysis. For petroleum, the activity data are divided into the following sectors: residential, commercial, and transportation (R,C,T); industrial; electric utility; and nonfuel use. For coal, the division is between electricity and other sectors (industrial combined with residential, commercial, and transportation). For natural gas the division is the same as for coal, plus flared gas. Methane and nitrous oxide are divided by source categories. For each source category, bias and random errors are aggregated by assuming an aggregate emission factor and a single scaling factor for activity data.

Because the underlying data are obtained from various EIA surveys, they have different levels of associated uncertainty. For example, the maximum bias error for coal activity associated with the electric power sector is estimated to be 4 percent, whereas the maximum bias error for coal activity associated with the other sectors is estimated to be 7 percent. This is because fuel use among the reporting electricity generators is well known, but for the other sectors (especially residential and commercial) the data are less reliable.

The table on page 18 outlines preliminary results from the Monte Carlo simulations. Monte Carlo simulations were carried out for each greenhouse gas separately, as well as all greenhouse gases as a group. Each column of the table denotes a separate simulation. Uncertainty about the simulated mean varies by type of gas. There is less uncertainty around the carbon dioxide simulated mean (-1.4 to 1.3 percent) than for methane (-15.6 to 16.0 percent) or nitrous oxide (-53.5 to 54.2 percent).

When uncertainty is expressed as a percentage of estimated 1999 emissions, the uncertainty becomes more skewed in the positive direction. This follows from the bias error assumptions above, which generally assume that emissions are underestimated. Denominating uncertainty as a percentage of estimated 1999 emissions yields the following uncertainty bands: carbon  
(continued on page 17)

<sup>a</sup>Intergovernmental Panel on Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (Oxford, UK: Oxford University Press, May 2000), p. 6.12.

<sup>b</sup>Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in EIA, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).



## Analysis of Uncertainty in Greenhouse Gas Emissions (Continued)

## Bias and Random Uncertainties Associated with EIA's Reported Greenhouse Gas Inventory Data, 1999

Source Category	Activity Data			Emissions Factors		
	Bias (Uniform)		Random	Bias (Uniform)		Random
	Minimum <sup>a</sup>	Maximum <sup>b</sup>		Minimum <sup>a</sup>	Maximum <sup>b</sup>	
Carbon Dioxide						
Natural Gas						
Other Sectors (R,C,I,T) . . . . .	0.5%	3.0%	0.5%	0.0%	0.0%	0.4%
Electric Utility . . . . .	0.5%	2.0%	0.5%	0.0%	0.0%	0.4%
Flared . . . . .	10.0%	25.0%	2.0%	10.0%	10.0%	5.0%
Coal						
Other Sectors (R,C,I,T) . . . . .	1.0%	7.0%	0.7%	1.0%	1.0%	0.5%
Electric Utility . . . . .	0.5%	4.0%	0.6%	1.0%	1.0%	0.5%
Petroleum						
R,C,T Sectors . . . . .	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Industrial . . . . .	2.0%	3.0%	0.6%	4.0%	4.0%	0.6%
Electric Utility (Heavy Oil, Light Oil, Petroleum Coke) . . . . .	0.5%	2.0%	0.5%	3.0%	3.0%	0.6%
Nonfuel Use . . . . .	1.0%	4.0%	0.6%	3.0%	3.0%	0.6%
U.S. Territories . . . . .	5.0%	10.0%	5.0%	1.0%	1.0%	0.5%
CO <sub>2</sub> in Natural Gas . . . . .	5.0%	5.0%	5.0%	30.0%	30.0%	5.0%
Bunkers . . . . .	10.0%	10.0%	0.2%	1.0%	1.0%	2.0%
Cement . . . . .	2.0%	4.0%	1.0%	3.0%	3.0%	1.0%
Other Industrial Sources . . . . .	5.0%	10.0%	3.0%	5.0%	5.0%	5.0%
Methane						
Coal						
Underground Coal Mines: Very Gassy . . . . .	5.0%	10.0%	20.0%	0.0%	0.0%	0.0%
Degasification and Underground Mines . . . . .	5.0%	10.0%	20.0%	35.0%	25.0%	5.0%
Surface Mines and Post-Mining Emissions . . . . .	10.0%	10.0%	10.0%	40.0%	100.0%	10.0%
Oil and Gas Systems						
Natural Gas Systems . . . . .	3.0%	5.0%	3.0%	40.0%	40.0%	5.0%
Petroleum Systems . . . . .	3.0%	5.0%	3.0%	50.0%	60.0%	5.0%
Combustion						
Residential and Commercial Wood . . . . .	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary and Mobile Combustion . . . . .	0.5%	2.8%	0.5%	30.0%	30.0%	15.0%
Waste Handling						
Landfills: Recovery Systems (Modeled) . . . . .	5.0%	20.0%	10.0%	25.0%	25.0%	10.0%
Landfills: Recovery Systems in Place (1992) . . . . .	10.0%	10.0%	7.0%	0.0%	0.0%	0.0%
Landfills: No Recovery Systems . . . . .	10.0%	30.0%	5.0%	50.0%	10.0%	10.0%
Wastewater Systems . . . . .	0.0%	3.0%	5.0%	55.0%	200.0%	10.0%
Agricultural Sources						
Livestock: Enteric Fermentation . . . . .	3.0%	5.0%	3.0%	10.0%	10.0%	10.0%
Livestock: Waste . . . . .	3.0%	5.0%	3.0%	30.0%	40.0%	10.0%
Rice . . . . .	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
Crop Residues . . . . .	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
Industrial Processes						
Chemicals and Steel and Iron . . . . .	3.0%	5.0%	3.0%	60.0%	60.0%	10.0%

See notes at end of table.

(continued on page 18)

# Analysis of Uncertainty in Greenhouse Gas Emissions (Continued)

## Bias and Random Uncertainties Associated with EIA's Reported Greenhouse Gas Inventory Data, 1999

Source Category	Activity Data			Emissions Factors		
	Bias (Uniform)		Random	Bias (Uniform)		Random
	Minimum <sup>a</sup>	Maximum <sup>b</sup>		Minimum <sup>a</sup>	Maximum <sup>b</sup>	
Nitrous Oxide						
Agricultural Sources						
Nitrogen Fertilization . . . . .	5.0%	10.0%	5.0%	90.0%	200.0%	10.0%
Animal Waste . . . . .	3.0%	5.0%	3.0%	90.0%	100.0%	10.0%
Crop Residues . . . . .	5.0%	10.0%	3.0%	60.0%	60.0%	20.0%
Energy Combustion						
Residential and Commercial Wood . . . . .	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary Combustion . . . . .	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%
Waste Combustion . . . . .	30.0%	30.0%	10.0%	90.0%	200.0%	15.0%
Mobile Sources . . . . .	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Waste Management . . . . .	2.0%	5.0%	5.0%	55.0%	200.0%	10.0%
Industrial Processes . . . . .	10.0%	10.0%	3.0%	55.0%	200.0%	10.0%

<sup>a</sup>The minimum bias is the relative change below the mean value.

<sup>b</sup>The maximum bias is the relative change above the mean value.

R, C, T, I = residential, commercial, transportation, and industrial. GHG = greenhouse gases.

Source: Energy Information Administration, annual data for 1999.

dioxide, -0.7 to 2.0 percent; methane, -2.8 to 33.7 percent; and nitrous oxide, -35.1 to 115.3 percent. When the uncertainty bands are expressed as a percentage of total estimated 1999 emissions,<sup>c</sup> the following uncertainty bands are derived: carbon dioxide, -0.6 to 1.7 percent; methane, -0.3 to 3.4 percent; and nitrous oxide, -1.9 to 6.3 percent.

The final column in the table below shows the Monte Carlo results when all the gases are simulated together. This simulations shows that total uncertainty about the simulated mean is -4.4 to 4.6 percent. Expressed as a percentage of total emissions, the uncertainty is -0.4 to 9.0 percent.

## Preliminary Results of Tier 2 Monte Carlo Uncertainty Analysis of EIA's Reported Greenhouse Gas Inventory Data, 1999

(Million Metric Tons Carbon Equivalent)

Gas	Carbon Dioxide	Methane	Nitrous Oxide	Total <sup>a</sup>
Estimated 1999 Value <sup>b</sup> . . . . .	1,526.8	180.7	98.8	1,806.3
Monte Carlo Simulated 1999 Mean <sup>c</sup> . . . . .	1,536.4	208.2	138.0	1,882.2
5th Percentile . . . . .	1,515.5	175.6	64.2	1,799.5
95th Percentile . . . . .	1,556.8	241.5	212.8	1,969.6
Total Uncertainty Around Simulated Mean . . . . .	41.3	65.9	148.6	170.1
Uncertainty as Percent of Simulated Mean . . . . .	-1.4% - 1.3%	-15.6% - 16.0%	-53.5% - 54.2%	-4.4% - 4.6%
Uncertainty as Percent of Estimated Value . . . . .	-0.7% - 2.0%	-2.8% - 33.7%	-35.1% - 115.3%	-0.4% - 9.0%
Uncertainty as Percent of Total Estimated Emissions <sup>d</sup> . . . . .	-0.6% - 1.7%	-0.3% - 3.4%	-1.9% - 6.3%	-0.4% - 9.0%

<sup>a</sup>Note that, with the exception of estimated 1999 values, columns will not sum to total because each individual column denotes a separate simulation. Monte Carlo simulations were carried out for all the gases separately and as a group.

<sup>b</sup>Estimated 1999 emissions from Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

<sup>c</sup>Monte Carlo simulations using 1999 EIA data from Science Applications International Corporation, prepared for the Energy Information Administration, *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emissions and Related Support Work* (Washington, DC, May 2001).

<sup>d</sup>Expressed as a percentage of total carbon dioxide, methane, and nitrous oxide emissions in 1999. Note that this excludes HFC, PFC and SF<sub>6</sub> emissions, which were not included in the uncertainty analysis.

<sup>c</sup>Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in *EIA, Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).